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Complex application of magnetic and magnetoacoustic parameters in the structuroscopy of ferromagnetic materials

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Abstract. The set of magnetic parameters and amplitude-frequency spectral characteristics of magnetoacoustic emission (MAE) of a large group of metal ferromagnetic materials differing in their physical properties and size are investigated. It is shown that the change in critical fields determined by the shape of the magnetization curve and the hysteresis loop of bulk samples with an increase in the annealing temperature of cold-deformed steel 20G is 1.5–3 times greater than the change in such well-known parameters for estimating the stress-strain state, such as coercive force and residual magnetic induction. It has been established that the amplitude of magnetoacoustic emission correlates with the residual magnetic induction, which makes it possible to recommend the complex application of these testing parameters in scanning systems of structuroscopy of ferromagnetic materials.

1. Introduction

Magnetic structuroscopy also known as magnetic structural analysis and materials characterization of ferromagnets are based on the correlation between magnetic and mechanical properties. A variation in the structural-phase state of the steel leads to a change in the strength properties of the steel, which leads to a significant change in the magnetic properties of the ferromagnet. [1]. However, the use of magnetic testing parameters alone is often not sufficient for the complete determination of the structural-phase state of steel products. Additional information can be acquired by parameters related to the interaction of moving domain walls with defects of the crystal structure. Magnetoacoustic emission (MAE) refers to the entire set of elastic vibrations that occur in a ferromagnet during its magnetization reversal. MAE can occur due to electromagnetic-acoustic conversion by the action of eddy currents and due to magnetostrictive excitation of elastic vibrations by an irreversible displacement of domain boundaries. The first mechanism does not manifest itself at low (units of Hz) frequency of the magnetization reversal due to the smallness of eddy currents. The second mechanism, sometimes called magnetic noise, is associated with the Barkhausen effect, and unlike the well-known electromagnetic registration of Barkhausen signals, MAE allows to record jumps of domain walls not only near the surface but also in the bulk of the material. Magnetoacoustic emission carries information both about local magnetostriction interactions associated with irreversible displacements of 90-degree domain boundaries and about the resulting magnetostrictive change in the size of a ferromagnet, which can be considered the third mechanism of MAE [2-4].

Magnetoacoustic emission is used to study the microstructure of steels and alloys [5,6], to study the domain structure and the relationship of magnetic and acoustic properties of ferromagnetic materials [7], as well as to determine the structural-phase [8] and stress-strain state of materials and objects



[9,10]. In works [2,3] it was shown that it is expedient to perform a juxtaposition of MAE signals with hysteresis magnetic characteristics of materials and to analyze the amplitude-frequency spectral characteristics of magnetoacoustic emission while ensuring the registration of a magnetoacoustic signal by broadband piezoelectric transducers.

Thus, summing up, the actual task is to develop multiparameter and complex techniques (i.e., based on the registration of parameters of different physical nature) and appropriate equipment for nondestructive testing. This justifies the aim of this work, to demonstrate the possibility of the complex application of magnetic and magnetoacoustic parameters in the structuroscopy of ferromagnetic materials.

2. Materials and experimental methods

To assess the effect of the stress-strain state on the MAE signal, samples from steels 20G and 70G were selected, the stress-strain state of which was varied over a wide range by cold plastic deformation by rolling up to 40% and 63%, respectively (by section change), and then annealing at different temperatures in the range from 20 to 800 °C for 1 hour, followed by air cooling. Then the samples were ground to remove the dross and the decarburized layer. The final sizes of 20G steel samples were 4x10,2x69 mm, and 70G steel - 6x9,5x88 mm.

The magnetic properties of the substance of the samples were determined two ways using the measuring complex REMAGRAPH C-500 manufactured by Magnet-Physik Dr. Steingroever GmbH, Germany and using mobile hardware-software system of multiparameter electromagnetic testing DIUS-1.15M [11,12]. The error in measuring the magnetization did not exceed 2%, the error in measuring the field was 1%.

To study the relationship between magnetic and magnetoacoustic parameters two groups of annealed 20G and 70G steel samples were used. Main magnetic properties and Brinell hardness of these steel samples are presented in figure 1. To study the dependence of magnetoacoustic emission on the frequency of magnetization reversal, samples were made of 10 and 95Cr18 steel grades. Samples were in the form of plates $4.6 \times 40.1 \times 90$ mm in size, differing in structural-phase composition and, accordingly, in magnetic properties. Chemical composition of all steels is shown in table 1. The 10 and 95Cr18 steels plates were quenched and tempered at various temperatures (T_{que} and T_{tem} , respectively) as shown in table 2.

Table 1. Chemical composition of studied steels, % (mass fr.).

Steel	C	Si	Mn	Cr	Ni
20G	0.21	0.27	1.0	0.3	0.3
70G	0.69	0.25	1.0	0.21	0.3
10	0.11	0.28	0.44	0.09	0.14
95Cr18	0.97	0.26	0.47	18.1	0.3

Table 2. Magnetic parameters and Brinell hardness of heat-treated steel plates.

Steel	T_{que} (°C)	T_{tem} (°C)	Br (T)	Hc (A/cm)	HB
10	930	400	1.1	8.9	269
		600	1.5	6.0	192
95Cr18	1070	200	0.5	74.5	601
		550	0.8	28.0	534

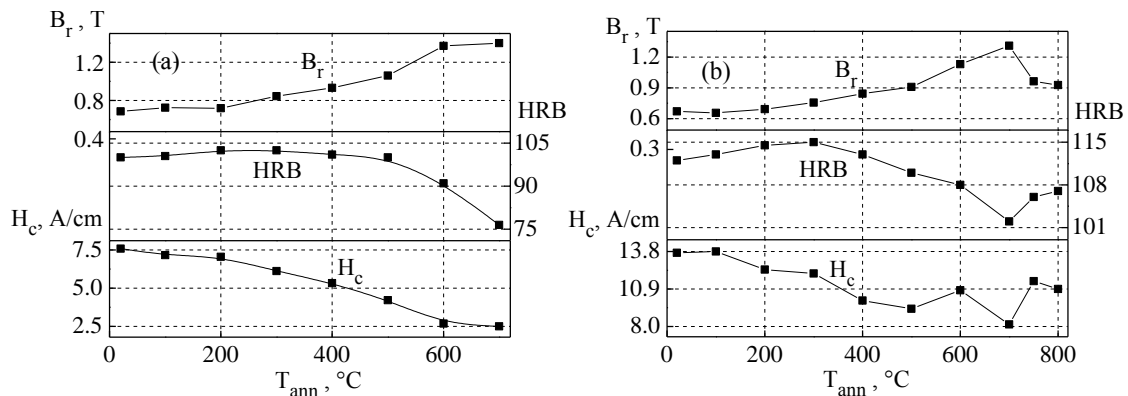


Figure 1. The dependences of the residual magnetic induction, Brinell hardness and coercive force of the annealed 20G (a) and 70G (b) steels measured using a Remagraph C-500.

3. Results and discussion

To assess the possibility of the use of locally measured magnetic parameters for the quality of annealing and steel strength testing, local measurements were made of the residual magnetic induction (figure 2) and coercive return induction (i.e., the induction remaining after switching off the coercive field, figure 2) on samples of steel 20G and 70G using the Remagraph C-500 and hardware-software system DIUS-1.15M. As can be seen from the figure 1, there is a monotonous increase (almost twofold increase) in the residual magnetic induction with an increase in the annealing temperature of steel 20G. For steel 70G, the dependence of the residual magnetic induction Br on the annealing temperature is close to linear, and the Br value of this steel decreases by half with an increase in the annealing temperature to 700 °C.

However, it should be noted that a necessary condition for ensuring the possibility of a local measurement of the residual magnetic induction of a substance is good contact of the surface of the test object and the poles of the attachable electromagnet. The presence of a gap in the “transducer-object” circuit can affect not only the magnitude, but also the structural sensitivity of the measured magnetic parameter [13].

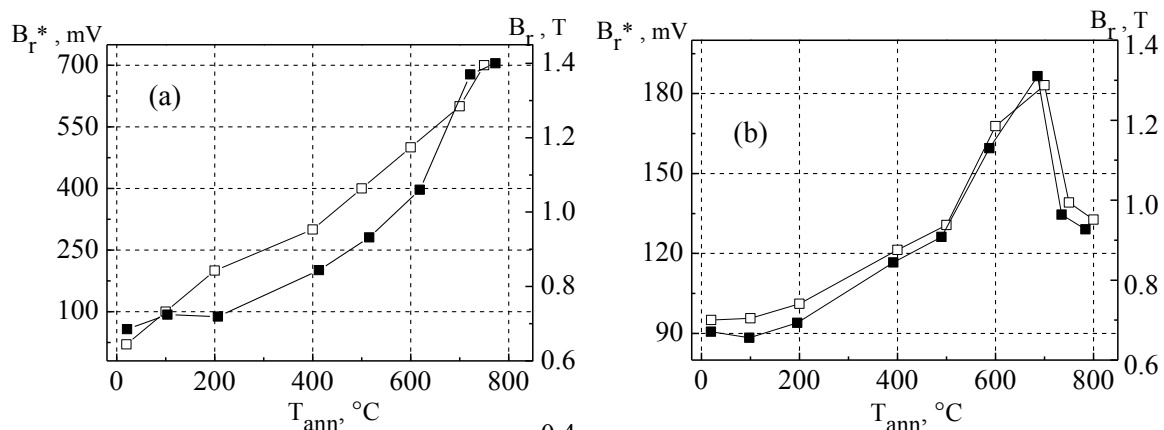


Figure 2. The dependences of the residual magnetic induction of a steel’s substance, measured using a Remagraph C-500 (filled squares) and DIUS-1.15M (hollow squares) on the annealing temperature of steel 20G (a) and 70G (b).

For the induction of coercive return, there are already local measurement methods in the presence of a gap between the surface of the test object and the measuring transducer [11]. The Br value locally measured using an attachable measuring transducer correlates well with the value of the residual magnetic induction measured by Remagraph C-500. Monotonous increase of Br with an increase of annealing temperature to 700 °C, makes locally measured residual magnetic induction a suitable

parameter for annealing temperature testing. However, the coercive return induction changes differently with increasing of annealing temperature: for low carbon steel 20G practically twofold, and for steel 70G the change is only about 25%.

For steel 70G at annealing temperatures higher than 700 °C, the magnitude of the residual magnetic induction falls to values typical of lower annealing temperatures (of the order of 500-550 °C), which can lead to an incorrect assessment of annealing temperature or steel's strength only from this magnetic parameter. But, as can be seen from figure 3, such “overheating” during annealing of the 70G steel can be easily detected by an elevated level of the magnitude of induction of coercive return B_{hc} .

Thus, for steel 20G, the quality control of annealing should be carried out according to the residual magnetic induction Br specifically, and for steel 70G, two-parameter control with a joint analysis of the residual magnetic induction Br and induction of coercive return B_{hc} is necessary.

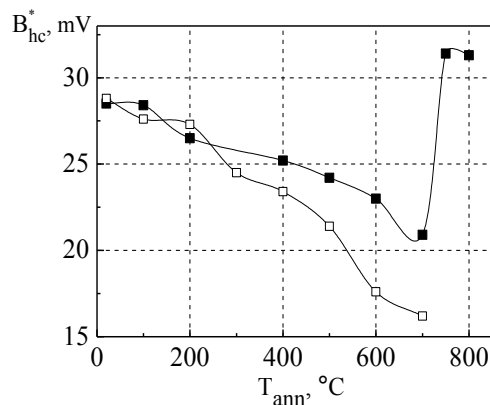


Figure 3. The dependence of coercive return induction on steels 70G (filled squares) and 20G (hollow squares) annealing temperature.

In the setup described in the previous section, magnetoacoustic measurements were carried out in order to establish the nature of the MAE amplitude dependence on the magnetization reversal frequency $UMA_{E(f_{rm})}$ of a group of samples with different structural-phase states (see table 1). As can be seen from figure 4, for all samples from steels 10 and 95Cr18, the presence of a maximum is characteristic of the dependence of the MAE amplitude on the frequency of the alternating field.

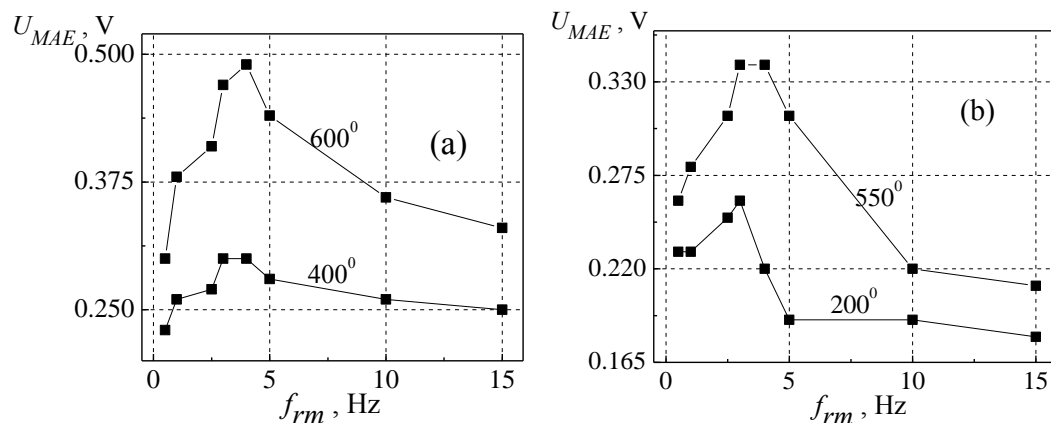


Figure 4. Dependences of MAE amplitude of quenched and tempered at different temperatures samples of (a) steel 10 and steel 95Cr18 (b) on the frequency of the remagnetizing field. Tempering temperatures of samples shown on the figure.

When the field frequency decreases below 0.5 Hz, the signal decreases sharply to the noise level. With increasing frequency, the signal decreases quite quickly and at a frequency of 15 Hz and more, it also becomes comparable with the noise level. The nonmonotonic dependence of the MAE amplitude on the frequency of the alternating field and the “resonant” frequency of MAE, falling at frequencies

of 3–4 Hz, are observed for all samples of the group, despite the differences in carbon content and different tempering temperatures [3,4].

For annealed steels 20G and 70G, the amplitude parameters of magnetoacoustic emission are more promising. Figure 5 shows the dependences of the amplitude of MAE and the residual magnetic induction on the annealing temperature of samples from cold-formed and annealed steel 70G.

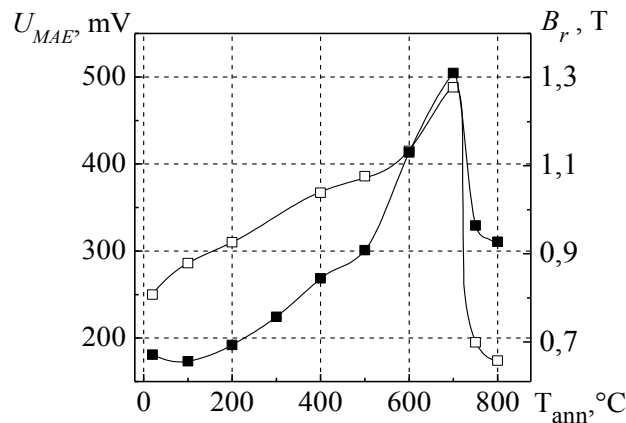


Figure 5. Dependences of the amplitude of magnetoacoustic emission (hollow squares) and residual magnetic induction (filled squares) on the annealing temperature of steel 70G.

The figure 5 shows a clear correlation between the residual magnetic induction and the amplitude of the magnetoacoustic emission. With an increase in the annealing temperature in the range of (20-700) $^\circ\text{C}$, the value U_{MAE} of steel 70G increases approximately 2 times, which is comparable with the change in the residual magnetic induction of these materials.

In accordance with the method [14], which consists in constructing tangents to the experimentally determined magnetic measurements of the magnetization curve, as well as the "hysteresis-free magnetization curve" obtained by averaging the hysteresis loop points, the critical fields H_k^l and H_k^c for cold-deformed and annealed steel 20G were determined. The results are presented in figure 6.

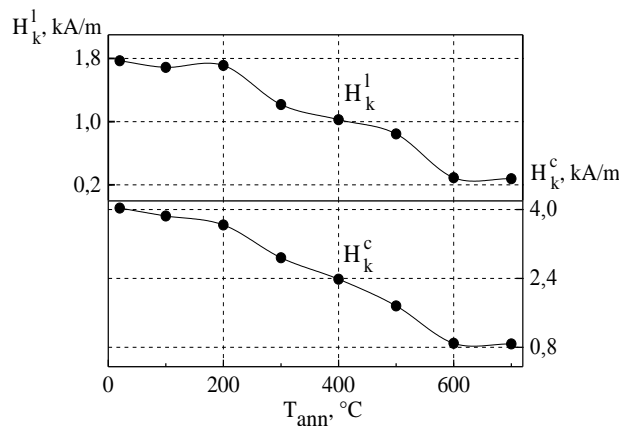


Figure 6. Dependences of magnetic properties on the annealing temperature of cold-deformed steel samples 20G.

As can be seen from figure 1 (a) the coercive force decreases by about 3 times, and the residual induction increases by 2 times with an increase in the annealing temperature of 20G steel from 20 to 700 $^\circ\text{C}$. At the same time, the value H_k^c monotonously decreases by 4.5 times, and the value H_k^l – by 6.4 times. It follows that the H_k^l and H_k^c parameters are more sensitive to changes in the stress-strain state of steel 20G, than the traditional residual magnetic induction and coercive force. This result can be explained by the fact that the quantities and are determined by the shape of the magnetization curve and the hysteresis loop in the region close to the technical saturation, i.e. in the area of prevailing displacements of 90-degree domain boundaries.

4. Conclusion

It is shown that the residual magnetic induction and the induction of the coercive return are sufficiently universal control parameters of annealing of cold-formed steels. These control parameters can be used both separately in one-parameter control and jointly in two-parameter control.

The presence of a correlation between the residual magnetic induction of a substance and the amplitude of the magnetoacoustic emission of annealed steel 20G and 70G was established. The MAE amplitude and residual magnetic induction could be used in complex technique of the structural analysis of ferromagnetic steels.

It is shown that the change in critical fields H_k^c and H_k^l with an increase in the annealing temperature of cold-deformed steel 20G is 1.5–3 times greater than the change in such well-known parameters for estimating the stress-strain state, such as coercive force and residual magnetic induction.

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